Int J Life Cycle Assess (2010) 15:927–937
DOI 10.1007/s11367-010-0226-x

LCA FOR FOOD PRODUCTS

Life cycle assessment of Australian sugarcane production with a focus on sugarcane growing

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Received: 8 May 2010 / Accepted: 6 July 2010 / Published online: 27 July 2010

Abstract
Purpose Past life cycle assessments (LCA) of sugarcane (*Saccharum officinarum*) production have commonly been based on limited datasets, and variability has not been well described. In this work, Australian sugarcane production was assessed more comprehensively in order to generate a robust set of LCA results for use in subsequent assessments of sugarcane products and also to investigate: (1) variability due to regional differences, (2) factors influencing variability, and (3) significance of the impacts.
Methods An average scenario for Australian sugarcane production was modeled based on data for the state of Queensland (98% of Australian production). Life cycle impact assessment (LCIA) results were generated using Impact 2002+, modified to be more representative of Australian conditions, and with the inclusion of water use and land use indicators. A Monte Carlo uncertainty analysis, using minimum and maximum values for production data, was undertaken to evaluate variability. Different regional production practices were also modeled to identify factors that influence variability. Normalization aimed to show the significance of total Australian sugarcane production relative to total Australian impacts.
Results and discussion Considerable variability was found in the LCIA results, with the key variables being yield, N use efficiency, the susceptibility of soils to N leakage, irrigation (water and energy intensity), and pre-harvest burning. N leakage was found to be an important issue that influences a range of impact categories. When normalized against total national impacts, water use and land use appear to be the most significant impacts (based on simple indicators of consumption), followed by eutrophication potential, acidification potential, and respiratory impacts, whereas non-renewable energy input and global warming are less significant. The results suggest that toxicity impacts are insignificant; however, this may not be supported by other observations that link pesticide loss from sugarcane to toxicity concerns in receiving waters and is a subject for further research.
Conclusions and recommendations The potential for significant variability in the impacts from sugarcane growing suggests a need for LCAs of sugarcane systems to consider ranges for key variables. The key variables and significant impacts identified in this work can guide data collection priorities for future assessment of sugarcane and possibly other Australian cropping systems. To further develop LCA as a useful predictive tool for Australian agricultural systems, further development and testing of impact assessment models for eutrophication, toxicity, and land and water resource depletion appropriate for Australia and its subregions will be required.

Keywords Agriculture · Crop · Environmental impact · Nitrogen · *Saccharum officinarum* · Sugarcane growing · Sugarcane production · Variability

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1 Background, aim, and scope

Sugarcane is grown over large areas in tropical regions of many countries around the world, mainly for sugar

(sucrose) for human consumption. However, a diverse range of other products such as electricity, fuels, organic chemicals, and paper can also be derived from it or its products (Paturau 1989; Manohar Rao 1997). As the value of sugarcane as a source of renewable energy, bio-fuels and bio-materials, as well as a food crop, is becoming more widely recognized (Miller et al. 2007; von Blottnitz and Curran 2007; Renouf et al. 2008), interest in the environmental impacts of sugarcane and its products is growing. This is confirmed by the number of life cycle assessments (LCA) of sugarcane products in recent years (Ramjeawon 2004; Botha and von Blottnitz 2006; Macedo et al. 2008; Nguyen and Gheewala 2008; Ramjeawon 2008; Contreras 2009; Luo et al. 2009; Ometto et al. 2009).

The sugarcane growing phase has been identified in all of these past sugarcane LCA studies to be the main contributor to the environmental impacts in the life cycle of sugarcane products. However, assessments of the growing phase in past studies have commonly been based on limited datasets, and variability in the production process has not been well described. Variability in agricultural processes has been identified to be significant (Ferret et al. 2004; Canals et al. 2006) due to the dynamic, natural processes on which they depend and the range of different farming practices. It is important, therefore, to have more comprehensive information about the agricultural phase of sugarcane production, to allow more robust evaluation of sugarcane products and systems.

In this work, LCA was used to assess the environmental impact of sugarcane production in Australia. A comprehensive assessment was possible due to the availability of a large industry dataset for sugarcane growing and recent research efforts in measuring gaseous emissions from sugarcane fields. The primary purpose was to generate a robust set of LCA data for sugarcane growing that could be used in subsequent assessments of Australian sugarcane products. However, it also aimed to advance the application of LCA to sugarcane systems by assessing the growing phase more comprehensively and by examining the key factors that influence the results, in particular variability due to different regional conditions and the impacts of nitrogen. This paper presents LCA of Australian sugarcane up to the delivery of the harvested cane to the sugar mill.

Sugarcane cultivation in Australia is concentrated along the east coast of Queensland, particularly in the central and northern areas, with some smaller production areas in northern New South Wales. This study used data for Queensland, which produces 98% of the total national cane crop. Therefore, the results can be taken to represent Australian production in general. Sugarcane is grown from cuttings (seed sugarcane) placed into well-cultivated soils, and the first year's growth is referred to as plant cane. After harvesting, the crop is allowed to re-grow to produce several ratoon crops, which are harvested in subsequent years at approximately 12 monthly intervals. The overall growing cycle is around 6 years, made up of one plant crop, four or five ratoon crops, and in some regions a fallow period. Data and results in this paper are averages over a crop cycle.

Sugarcane production in Australia is highly mechanized, employing machinery for all stages of crop cultivation, mechanical harvesting, and truck and rail transport of the harvested sugarcane to the mill. Nutrients for crop growth are applied as synthetic fertilizer, although some farms apply sugar mill residues (mill mud and ash) and dunder from ethanol fermentation as soil ameliorants or supplementary sources of nutrients. Crop protection chemicals are applied to control insect pests and weeds. Around 60% (by weight) of the crop is irrigated (C4ES Pty Ltd 2004), depending on the region and the season. Around 39% (by weight) of the crop is burnt prior to harvest (C4ES Pty Ltd 2004) with no retention of crop residues ("trash") in the field. The other 61% is harvested "green," with trash retained in the field. Harvested sugarcane is transported to the 23 sugar mills in Queensland, mostly by rail using the dedicated sugarcane rail network, and to a lesser extent by road trucks. Sugarcane production in Australia is more "industrialized" than in most other sugarcane growing countries, and the industry has traditionally placed a strong emphasis on maximizing crop and sugar yields.

The system boundary includes all processes from field preparation through to harvesting and transport of sugarcane to mills and associated inputs. The functional unit is 1 tonne of sugarcane delivered to mill. On-farm capital goods associated with sugarcane growing (tractors, harvesters, farm buildings, etc.) and the sugarcane rail system (track, locomotives, bins) were included, since capital goods are known to be significant for agricultural systems (Audsley et al. 1994; Wegener Sleeswifjk et al. 1996; Mattsson 1999). The assessment is based on existing sugarcane production, so pre-clearing of land is not in the system boundary.

Emissions of nitrogen (N), phosphorous (P), and pesticides from sugarcane fields have been included, as have the release of carbon dioxide from liming and losses of sugar to water that occur during harvesting. Methane uptake and/or release from sugarcane fields, as previously reported by (Weier 1998), was not included as more recent research suggests there is no net flux of methane from sugarcane fields (Denmead et al. 2010). Differences in soil carbon accumulation under different sugarcane growing regimes have not been included due to lack of data. Carbon dioxide released from the pre-harvest burning of sugarcane and from urea decomposition has not been included since both sources are regarded as a short-term release (IPCC 2006). The possible transfer of contaminants to soil from

abrasion of farm machinery tires and cultivator tines has not been included.

2 Method

2.1 Definition of average and regional cane growing scenarios

An “average” scenario was modeled based on average production data for the state of Queensland, along with minimum and maximum values to determine the overall variability. A number of different sugarcane growing regions were also modeled to assess the nature of variability under different regional conditions. In an earlier attempt to describe variability, it was assumed that the intensity of resource inputs per hectare would be the key factor influencing variability, and two regions representing extremes in this respect were modeled (Wet Tropics and Burdekin) (Renouf 2006). However, other factors were subsequently found to be more important predictors of impacts—environmental conditions (climate and soil type), nitrogen to yield ratios (which influence field emissions of N), extent and type of irrigation, and the extent to which sugarcane is burnt prior to harvest. Therefore, a wider range of regional scenarios were modeled to evaluate the influencing factors more carefully.

2.2 Data and data sources

Data for the quantities of inputs used in sugarcane production were sourced mainly from a survey of sugarcane growers (Milford and Pfeffer 2002) and industry statistics. The data are presented in Table 1 along with their sources and assumptions. Wherever possible, state average figures were calculated as sugarcane-weighted averages, meaning the data contributing to the average were weighted by the relevant regional sugarcane production. Where this was not possible, the best available estimates of industry averages were used. Data for background processes (fertilizer and pesticide production, fuel and electricity production, transport and machinery operations, and materials for the sugarcane rail tracks) were mainly sourced from the Australian Life Cycle Inventory Database (Life Cycle Strategies Pty 2007). Data for the production of farm machinery, harvesters, and rail locomotives were sourced from the ecoinvent database (Life Cycle Inventories 2009).

Emissions from sugarcane fields (N species, P species, pesticides, and sugar) were derived from the published findings from field measurement trials and simulation modeling undertaken for Queensland sugarcane and are presented in Table 2. These field emissions vary considerably due to complex interactions between the soil, the crop, and the climatic environment. For N, regional differences in rates of dentrification (nitrous oxide and nitrogen oxides) and leaching (nitrate) are becoming better understood, and it was possible to derive regional emission factors for these emissions. For other emissions (P, pesticides, and sugar loss via runoff and NH_4 loss by volatilization), there is less information and it was not possible to make regional distinctions, and the average emission factors were applied for all regional scenarios. It was not possible to obtain representative data for N loss via runoff from sugarcane fields, and this is a limitation of the field emissions estimates.

The direct N_2O–N emission factors for soil denitrification used in this study (see Table 2) are higher than the generic figure of 1.25% recommended by the Australian Greenhouse Office methodology (National Greenhouse Gas Inventory 2007). The propensity for high N_2O emissions from Australian sugarcane compared with other crops has been observed (Thorburn et al. 2010) and has been attributed to it being grown in conditions conducive to high rates of dentrification—high N availability, high soil moisture, high temperatures, and the presence of organic matter. Research aimed at better understanding N_2O emissions intensity of Australian sugarcane is ongoing, and there is still considerable uncertainty in relation to the emissions factors used in this study.

2.3 Impact assessment

Life cycle impact assessment (LCIA) results were generated using the Impact 2002+ model (Jolliet et al. 2003) using Simapro (Version 7.1), but with the following additions, modifications, and omissions, to be more representative of Australian conditions and the system being studied:

- Results were not generated for ionizing radiation and ozone layer depletion as they were not considered applicable for the system being studied.
- Global warming potential was characterized using the more commonly recognized factors from the International Panel on Climate Change for a 100-year time horizon (IPCC 2003), so that subsequent assessments of sugarcane products, which use the results from this work, could be compared with results from other studies.
- Eutrophication potential was characterized assuming that receiving waters are limited by both N and P, due to the lack of information about the eutrophication susceptibility of Australian receiving waters.
- Land use was assessed using a basic indicator of land occupied, not land transformation.
- Water use was assessed using a basic indicator of water consumption, with no assessment of resource depletion.

Mid-point indicators were considered more appropriate than end-point indicators as they offered more transparency to the evaluation of contributing factors and variability.

Table 1 Production parameters for sugarcane production (per tonne of sugarcane delivered to mill)

Inputs	Unit	State average	State min	State max
Energy input				
Diesel for tractors[a]	MJ	87.9	12.7	221.8
Diesel for harvest[b]	MJ	54.0	38.6	65.6
Electricity for irrigation[a]	kWh	8.1	0	30.1
Water use for irrigation[c]	kL	37.2	0	208.3
Seed cane[a]	kg	12.1	1.1	41.7
Fertilizers and agro-chemicals				
N (as N)[a]	kg	2.0	1.0	3.0
N (as urea)[a]	kg	3.7	0.2	8.4
P (as P)[a]	kg	0.2	0	0.7
P (as DAP)[a]	kg	1.2	0	4.0
Potassium chloride[a]	kg	1.3	0	5.2
Ammonium sulfate[a]	kg	0.5	0	2.6
Lime (limestone)[a]	kg	2.1	0	17.9
Pesticide—active ingredient[a]	g	24.8	2.8	88.8
Transport of farming inputs				
Shipping[d]	t.km	60.1	2.1	205.6
Articulated truck[d]	t.km	3.0	0.04	10.2
Rigid truck[d]	t.km	0.1	0.004	0.4
Burnt cane harvesting[e]	%	39	0	100
Green cane harvesting[e]	%	61	0	100
Transport of crop to mill				
Rail[f]	t.km	17.5	0	22.0
Road[f]	t.km	4.6	0	47.2
Production of capital goods				
Tractor[g, k]	kg	0.08	0.04	0.17
Farm implements[g, k]	kg	0.02	0.01	0.08
Farm shed[g, k]	m^2	0.0003	0.0001	0.0017
Harvester[h, i, k]	kg	0.02		
Trailer[h, i, k]	kg	0.02		
Cane rail locomotive[h, j, k]	unit	2E-7		
Cane rail tracks[h, j, l]	m	0.003		
Sugarcane yield[m]	t/ha	85	60	110

For brevity, the data for the regional scenario are not shown

[a] Survey data for a sample of Queensland sugarcane growers (n=94) (Milford and Pfeffer 2002). State average figures are weighted average

[b] Personal communication with Queensland Harvesters. State average is best available industry average. This includes harvest and haulout

[c] Water use is supplementary water from dams, groundwater, irrigation schemes, etc. and does not include rainfall. Data from industry audit of sugarcane growing practices (C4ES Pty Ltd 2004). State average is a weighted average.

[d] Transportation of urea (from Middle East), diammonium phosphate (from central-western Queensland), potassium chloride (from Canada), ammonium sulfate (from Brisbane), lime (from central Queensland), and pesticides (from Europe via southern Australia), to farms via regional distributors in Cairns, Townsville, Mackay, and Brisbane. Figures calculated from quantities transported and weighted average transport distances

[e] Industry audit of sugarcane growing practices (C4ES Pty Ltd 2004). State average is % by weight of sugarcane harvested

[f] Cane transport data contained in industry review (Hildebrand (2002) Appendix C), based on weighted average haul distances

[g] Farm capital goods based on quantities present on average farm and years of service, then amortized over cane produced over total service life

[h] Harvesting and cane rail capital goods were based on the total state harvester fleet and cane rail system and years of service, then amortized over total state cane production over total service life. Therefore, only state average figures generated and apply to all regional scenarios

[i] Figures for harvesting capital goods based on personal communication with Queensland Harvesters

[j] Figures for cane rail capital goods based on information from the Light Railway Research Society of Australia (Browning 2007)

[k] Figures are expressed in the units used in the life cycle inventories databases used as the source

[l] Cane rail tracks constitute steel rails, timber sleepers, and ballast, but for brevity, individual quantities of these are not detailed here

[m] Industry statistics (Anon 2006). State average yield is a weighted average

Table 2 Emissions from sugarcane growing

Species emitted	Unit	State av.	State min	State max
To air from pre-harvest burning				
Methane (CH_4)[a,d]	g/t cane	90	–	–
Nitrous oxide (N_2O) [a,d]	g/t cane	6	–	–
Nitrogen oxide (NO_X) [a,d]	g/t cane	331	–	–
Ammonia (NH_3 and NH_4^+)[b,d]	g/t cane	120	–	–
Carbon monoxide (CO) [a,d]	g/t cane	3,944	–	–
Sulfur oxide (SO_X) [a,d]	g/t cane	41	–	–
NMVOC[a,d]	g/t cane	204	–	–
Phosphorous (P) [c,d]	% applied P	1.6	–	–
To air from soil denitrification				
Nitrous oxide (N_2O) direct[e,g]	% appl. N (as N_2O–N)	4	1.3	7
Nitrous oxide (N_2O) indirect[f,h]	%deposited NO_X–N and NH_3–N	0.01	0.01	0.01
Nitrogen oxides (NO_X) [g]	% appl. N (as NOx–N)	6	2	9
To air from fertilization and liming				
CO_2 from liming[h]	t CO_2/t lime	0.4	0.4	0.4
NH_3 from urea volatilization[i]	% appl. Urea N (as NH_4–N)	2.6	0.0	40.0
To water				
Nitrate via leaching[g]	% appl.N (as NO_3-N)	6.5	0.1	25.3
Phosphorous via runoff[c]	% appl. P (as P)	12.8	7.4	19.0
Pesticide via runoff[j]	% active ingredient	1.5	1.5	1.5
Sugar via runoff[k]	kg COD/tonne cane	4.3	2.9	12.2

For brevity, the data for the regional scenario is not shown

[a] Derived from the emissions estimation methodologies (NGGI 2007)

[b] Derived from measured emissions data for cane burning (Machado et al. 2008)

[c] Derived from a regional budget of phosphorous losses (Bloesch et al. 1997)

[d] Minimum and maximum figure were not available. Instead, uncertainty was estimated (as SD^2) using an uncertainty estimation tool

[e] Direct denitrification emissions are those generated directly from N fertilizer application

[f] Indirect denitrification emissions are those generated from deposited NO_X and NH_3 originating from denitrification and sugarcane burning

[g] Derived from APSIM modeling of nitrogen balances for sugarcane (Thorburn et al. 2010)

[h] Derived from the emissions estimation methodologies of the International Panel on Climate Change (IPCC 2006), Chapter 11

[i] Urea–N is prone to volatilization when surface-applied. When surface-applied, volatilization rates have been estimated to be around 20% of the exposed urea–N for trash-blanketed soils (Freney et al. 1994), and speculated to be around 5% for un-blanketed soils (Thorburn et al. 2005). The minimum is based on subsurface application, where no volatilization is assumed to occur. The maximum is based on surface application (broadcasting) to trash-blanketed soils, as practiced in some regions (Herbert). The average assumes urea is surface applied for only 25% of sugarcane and that 50% of this is dissolved into soil from rainfall (pers. comm, with industry extension officers) and not prone to volatilization, and volatilization weighted based on proportions of trash-blanketed to un-blanketed soils (61%:39%)

[j] Derived from Hamilton and Haydon (1996)

[k] Derived from measured losses of sugar during sugarcane harvesting reported by Rayment (2002)

Uncertainty ranges were generated for the average scenario using Monte Carlo analysis. The uncertainty analysis was based on the minimum and maximum figures shown in Tables 1 and 2, and undertaken over 500 runs to generate results falling within the 95% confidence limits. The uncertainty is mostly due to local differences in sugarcane production and, therefore, represents the overall statistical variability of sugarcane production systems in Queensland.

2.4 Normalization

Normalization was undertaken to show the significance of the impacts of sugarcane production. The LCIA results for the average scenario were scaled up to total annual sugarcane production for Australia (approximately 40 Mt/year, ranging between 30 and 50 Mt/year) and divided by total annual impacts for Australia, developed by Foley and Lant (2008). For water

and land use, "total consumptive use of water in the economy" from the National Water (2005) and total productive land use from the Rural Science (2006), respectively, were used.

2.5 Contributional analysis

A contributional analysis was undertaken to show the impact of individual farm and transport operations, which have been broadly categorized as follows:

- Farm machinery use refers to the operation of tractors and harvesters.
- Electricity for irrigation refers to the production of electricity used to pump water.
- Agro-chemical production refers to production of fertilizers, lime, and crop protection chemicals.
- Transport refers to all transport operations in the foreground system, including transport of sugarcane from farm to mill (by truck and/or rail) and transport of fertilizer and agro-chemicals from factory to farm.
- Capital goods refer to the production of farm buildings, machinery, and the sugarcane railway and its locomotives.
- Field emissions refer to releases from sugarcane fields, including nutrients (N and P), pesticides and herbicides, and sugar lost during harvest.
- Sugarcane burning refers to the pre-harvest burning of sugarcane.

3 Results and discussion

The characterized LCIA results for the average scenario are presented in Table 3, along with the ranges generated from the uncertainty analysis. The variability is due mostly to regional differences in growing conditions and practices. The nature of this variability can be seen in Fig. 1a–j, which show the contributional analysis for each scenario. The normalized results, which show the relative significance of the impacts are shown in Fig. 2.

3.1 Non-renewable energy input

Non-renewable energy (NRE) input to sugarcane production was found to contribute less than 0.5% of national fossil-energy use (Fig. 2). The key energy-consuming operations are the production of fertilizers, fuel use in machinery, and electricity input for irrigation (Fig. 1a). Since Queensland's electricity is coal-derived, this aspect also contributes to other impact categories (global warming potential and acidification potential). Electricity input for irrigation strongly influences the variability in NRE as well the other associated indicators (see Fig. 1) and was found to depend on the type of irrigation system (flood, spray, or trickle) rather than the quantity of water applied. The Burdekin region has the highest water use but it is applied using the less-energy intensive flood irrigation, compared with Bundaberg, for example, where less water is applied but more energy-intensive high-pressure spray systems are used. Where sugarcane is transported by road instead of by rail (as in the Wet Tropics scenario where hilly conditions make rail haulage difficult), the energy input for transport is higher. Urea production accounts for 84% of the energy used for agro-chemical production. Even though much of the fertilizer and agro-chemicals used by the industry are imported (around 75%), energy use in transport was insignificant. Capital goods were found to be significant (6% of NRE input), mainly due to the dedicated sugarcane railway commonly used to transport harvested sugarcane to mills.

Table 3 Characterized LCIA results, including 95% confidence limits, for the average scenario (per tonne sugarcane delivered to mill)

Method	Impact category	Unit	State average	Low (2.5%)	High (97.5%)
Impact 2002+	Non-renewable energy	MJ primary	536.8	436.0	859.0
	Eutrophication potential	kg $PO_{4(eq)}$	0.39	0.34	0.76
	Acidification (aquatic)	kg $SO_{2(eq)}$	0.83	0.68	1.58
	Acidification (terrestrial)	kg $SO_{2(eq)}$	5.28	4.2	10.4
	Respiratory inorganics	kg $PM_{2.5}$	0.14	0.11	0.22
	Respiratory organics	kg $\text{ethylene}_{(eq)}$	0.07	0.04	0.15
	Mineral extraction	MJ surplus	0.35	0.25	0.51
	Carcinogens	kg $C_2H_3Cl_{(eq)}$	0.19	0.14	0.28
	Non-Carcinogens	kg $C_2H_3Cl_{(eq)}$	0.20	0.17	0.36
	Aquatic ecotoxicity	kg $TEG_{(eq)}$	1,257.7	915.0	2100.0
	Terrestrial ecotoxicity	kg $TEG_{(eq)}$	225.3	189.0	349.0
IPCC 100 yrs	Global warming potential	kg $CO_{2(eq)}$	77.9	66.4	114.5
Other	Water use	kL	37.7	16.4	185.0
	Land use	ha	0.012	0.010	0.015

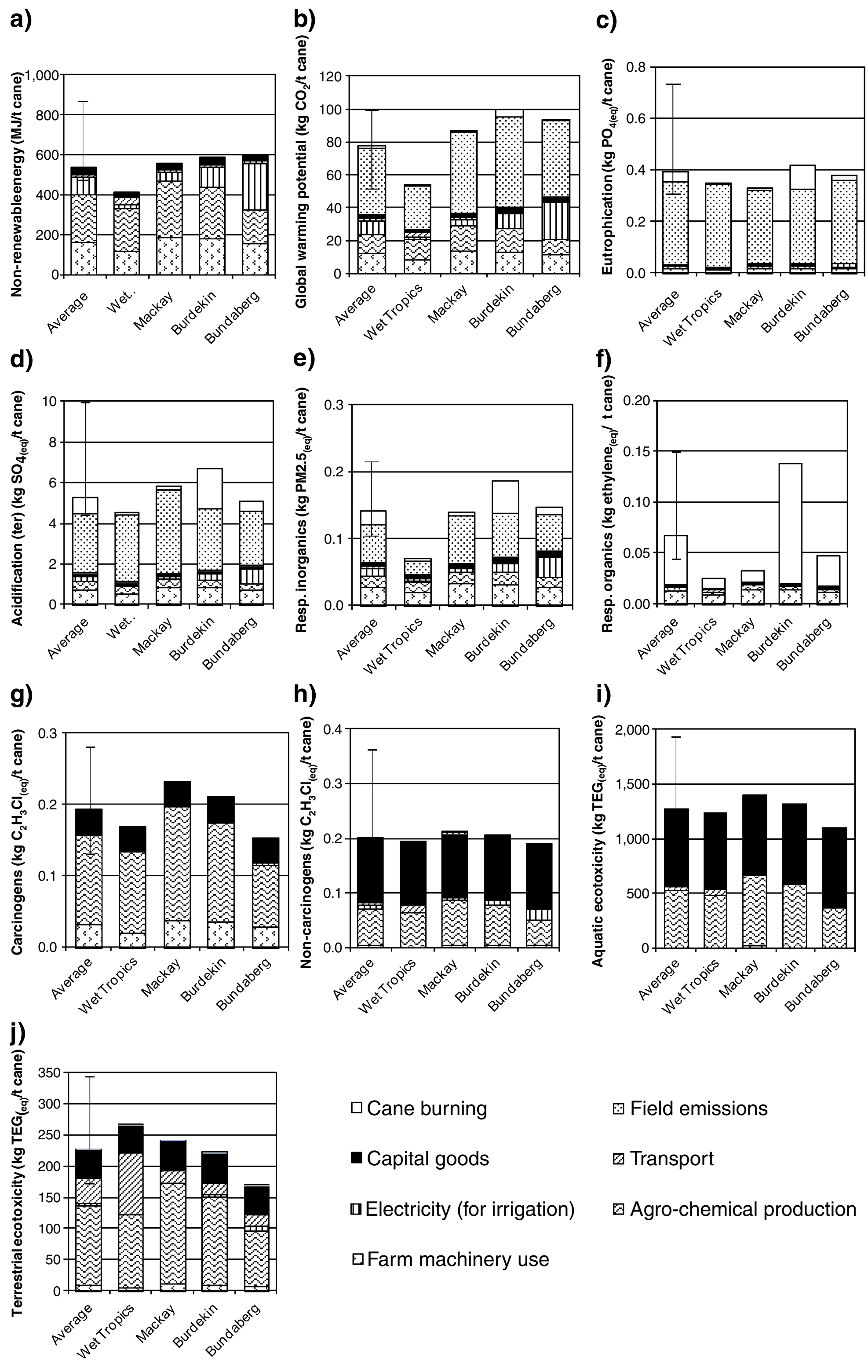
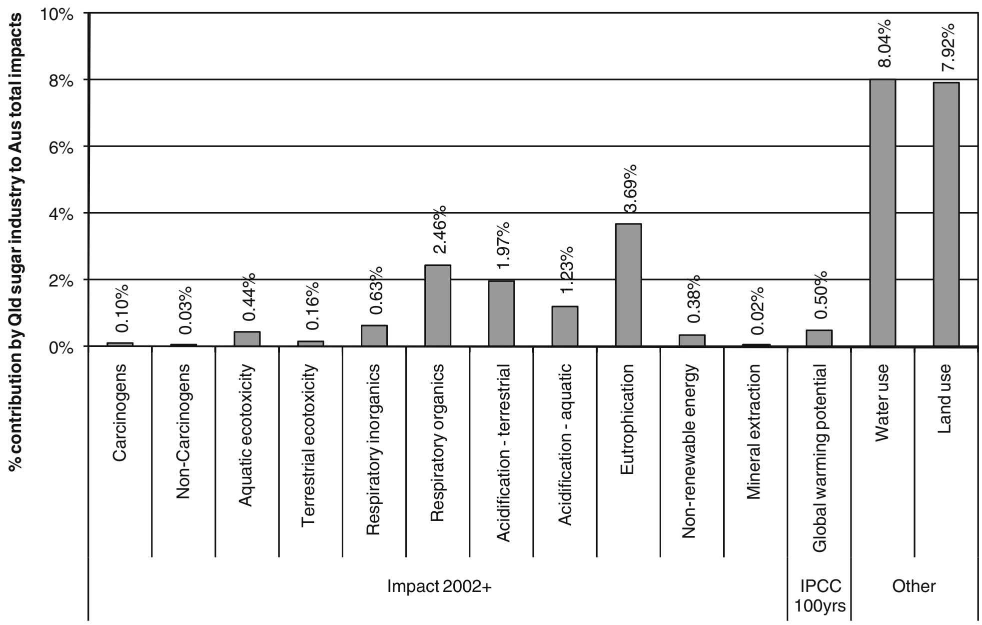


Fig. 1 Characterized LCIA results (per tonne sugarcane delivered to mill) and contributional analysis for the average and regional scenarios

3.2 Global warming potential

Around half of the global warming potential (GWP) of sugarcane production, based on the average scenario, is related to direct and indirect fossil-energy use (Fig. 1b) and mirrors the contributional analysis of NRE. The remainder is due to field emissions, which are mostly N_2O from soil denitrification but also CO_2 released from lime application. The N_2O emissions are the key factor influencing variability in GWP. The N_2O

Fig. 2 Normalized LCIA results: percent contribution of total Australian sugarcane production to total national impacts



emission factors derived in this study are higher than those used in other studies of sugarcane production for reasons described in section 2.2. Despite the potential for high N_2O emission rates, sugarcane production was found to contribute less than 1% of national GWP (see Fig. 2).

3.3 Eutrophication potential

The principal factor contributing to, and influencing variability in eutrophication potential (EP) is field emissions (see Fig. 1c), comprising P loss in runoff (37%), NO_3 leaching (30%), NO_X from denitrification (23%), and NH_4 volatilization from urea (10%). Other minor contributors are NO_X from sugarcane burning, transport and machinery operation, and electricity production. The non-inclusion of N loss via surface runoff was a limitation of the eutrophication assessment.

EP from sugarcane production was found to contribute around 3.7% of national EP (see Fig. 2). This is thought to be an overestimate because the impact assessment accounted for both N and P emissions under the assumption that receiving waters are limited by both N and P, which may not be the case, and the Australian totals used in the normalization do not include all diffuse emissions of nutrients for Australia (Foley and Lant 2008). Bearing in mind this uncertainty, the relatively high significance was not surprising. The potential impacts of nutrient releases from sugarcane growing on the health of coastal receiving waters in Queensland are recognized, and the industry is taking action to mitigate these impacts.

In relation to predicting the eutrophication potential, there is a need for an impact assessment model that is more appropriate for Queensland's aquatic receiving environments. For this work, it was necessary to assume that receiving waters are limited by both N and P, in the absence of more specific information, which is a very coarse representation of the situation. To date governments have emphasized reducing N releases to Queensland waterways, and this has been a strong driver for investment into environmental improvement initiatives such as advanced treatment of municipal wastewater, and reducing nitrogen export from sugarcane growing (through the Australian Government's Reef Rescue Package). However the eutrophication susceptibility of Australian coastal waters needs to be better understood and integrated into LCIA characterization factors.

3.4 Acidification potential

Results have been reported for both terrestrial acidification potential (AP-ter) and aquatic acidification potential (AP-aq; see Table 3). The contribution of sugarcane production to national AP-ter and AP-aq is between 1% and 2% (see Fig. 2). This may be overestimated, since the Australian totals against which the results were normalized do not include all diffuse emissions (Foley and Lant 2008). Only the contributional analysis for AP-ter is shown in Fig. 1d, for brevity, as the contributional breakdown is very similar for both AP-ter and AQ-aq. Less than half of AP is related to direct or indirect fossil-energy use and mirrors the contributional analysis of NRE. The remainder is due to field emissions (denitrified NOx and volatilised NH_4), and

sugarcane burning (NOx, SOx, and NH_4) which are also the key factors influencing variability in AP.

3.5 Respiratory inorganics and organics

Around half of the emissions of respiratory inorganics (RI) are related to direct or indirect fossil-energy use (see Fig. 1e), mirroring the contributional analysis of NRE. The remainder is due to field emissions (NO_X from soil denitrification processes, and NH_4 to a lesser extent) and sugarcane burning (NO_X, SO_X, and CO), which are the key factors influencing variability. RI from sugarcane production was found to contribute less than 1% of the national total (see Fig. 2), and this impact is highly localized.

For respiratory organics (RO) pre-harvest burning of cane is the main source (see Fig. 1f), with the main contributing substances being non-methanic volatile organic compounds (NMVOC) and methane. On average, sugarcane production contributes around 2% to national totals; but if sugarcane burning was not undertaken, this would reduce to less than 0.5%.

3.6 Eco- and human-toxicity indicators

The species contributing to the human toxicity (HT) results (carcinogens and non-carcinogens) are aromatic hydrocarbons, aldhydes, arsenic, dioxins, etc., derived from the provision of capital goods and machinery, the production of agro-chemicals, and exhaust emissions from farm machinery use. The species contributing to the ecotoxicity (ET) results are heavy metals from the manufacture of machinery and infrastructure components, and heavy metals from fertilizer and agro-chemical production.

Toxicity impacts of pesticide loss from fields (in particular the herbicides atrazine and diuron) did not register as significant in the contributional analysis (see Fig. 1g–j), which was unexpected. The normalized ET results (see Fig. 2) also suggest that the toxicity impacts from sugarcane production are not significant (less than 0.5%). However, there is a suggested link between the export of pesticides from sugarcane cultivation along the northeast tropical coast and water quality concerns in Queensland coastal waters, including the Great Barrier Reef lagoon (Brodie et al. 2008; Lewis et al. 2009). There appears, therefore, to be discrepancy between the ET potential predicted by this study and these field observations. One reason is that the inventory data used in this study may not adequately represent the pesticide losses. The other is that the impact assessment model for HT and ET impacts in Impact 2002+, which uses factors more relevant to Europe, is not useful for predicting these impacts in the Australian context. Preliminary toxicity results were also generated using the toxicity characterization models developed for Australia by Lundie et al. (2007). These results also showed toxicity impacts to be insignificant but have not been reported at this stage. Further assessment of toxicity using more representative data for pesticide losses and further testing of these emerging toxicity characterization models for Australia is warranted.

3.7 Water and land use

Most water and land used in the production of sugarcane is associated with the on-farm cultivation of sugarcane, with no significant contribution from background processes. Therefore, for brevity, the contributional analyses for these aspects have not been shown in Fig. 1. The water use and land use results (see Table 3) are based on simple indicators of consumption and occupation, respectively. On this basis, sugarcane production accounts for about 8% of national water and land use, making these appear to be the most significant aspects (see Fig. 2). However, these results do not present the impact of water and land use in terms of their potential to deplete resources. Further assessment is required once appropriate methodologies for Australia have been established. This could include the use of emerging water footprinting methods (Ridoutt et al. 2009), which consider the water stress status of the catchment from which the water is drawn.

4 Conclusions

This work has generated significant and novel data on many of the environmental impacts of Australian sugarcane production, to support subsequent assessments of Australian sugarcane products and systems. In particular, field emissions of nitrogen species (N_2O, NOx, NH_3, and NO_3) were assessed in more detail than in previous sugarcane LCAs and were found to make a significant contribution to a number of impact categories (GWP, EP, AP, RI). N emissions can be an important issue for sugarcane (and possibly other intensively cultivated tropical crops), since the tropical conditions in which it is commonly grown (high temperatures, high soil moisture) can be conducive to the nitrification/denitrification processes in soil that mobilize N (Thorburn et al. 2010). For Australian sugarcane, the high levels of N available in soils due to generous fertilizer application rates to achieve high crop yields further exacerbates the potential for N losses. The efficient management of N will bring multiple benefits for Australian sugarcane production. It would seem from the normalization results that the eutrophication effects of N loss to water are more significant than the global warming effects of N_2O emissions. However, there is a need to further develop eutrophication characterization factors to be

more appropriate for Queensland receiving waters, to give more certainty to the prediction of the eutrophication impacts.

Large variability was found in the LCIA results, which supports other observations of variability in agricultural cropping (Ferret et al. 2004; Canals et al. 2006). For intensive sugarcane cultivation such as that practiced in Australia, the key variables were found to be yield, N use efficiency (N–yield ratio), the susceptibility of soils to N leakage, irrigation (water and energy intensity), and pre-harvest burning. Some of the variability observed is due to natural differences in the climatic and soil conditions in different regions. This is the case for yield potential, irrigation intensity, and N losses. It may also be the case for pesticide loss, since pest control regimes can be dictated by climatic conditions. However, this was not fully assessed in this work. The other key causes of variability are production practices—type of irrigation system, intensity of tractor use, N use efficiency, and harvesting method (burnt versus green). This work has examined the influence of some production variables, but there is scope for further work. Transportation variables (transporting the crop and the farming inputs) were found to be insignificant.

Water use and land use appear to be the most significant aspects of Australian sugarcane production, when assessed using simple indicators of consumption. After them, eutrophication potential, acidification, and respiratory impacts (from sugarcane burning) are significant, whereas consumption of non-renewable energy and global warming potential are less significance. The results suggest that toxicity impacts from sugar growing are of little significance; however, this is may not be supported by other assessments of the receiving coastal waters.

5 Recommendations and perspectives

The significant variability present in sugarcane growing, particularly that related to field emissions, suggests the need for LCAs of sugarcane systems and products to consider ranges (uncertainty) for key variables. The key variables identified in this work can guide assessment priorities for future work on sugarcane systems. While water use and land use have been identified as the most significant aspects of Australian sugarcane production; further assessment using more refined methods for water resource depletion and land utilization is warranted. Given the proximity of Australian sugarcane production to sensitive aquatic environments (the Great Barrier Reef), the prediction of eutrophication and toxicity impacts from nutrient and pesticide releases requires further investigation. These impacts are also important for agricultural cropping more broadly. It will be difficult for LCA to develop as a useful predictive tool for Australian agriculture without development of eutrophication and toxicity impact assessment models appropriate for Australia and its subregions.

Acknowledgement This research was undertaken as part of a PhD project in the School of Geography, Planning, and Environmental Management at The University of Queensland. The authors acknowledge the funding provided by the Cooperative Research Centre for Sugar Industry Innovation through Biotechnology (CRC SIIB). Recognition needs to be given to the numerous people and organizations that contributed data and technical guidance to this project including Queensland Canegrowers, Queensland Caneharvesters, Light Railway Research Society of Australia, CSIRO Sustainable Ecosystems, Queensland Department of Primary Industries and Fisheries, BSES Limited, and the Fertilizer Industry Federation of Australia.

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